100 YEARS TRB
MOVING IDEAS: ADVANCING SOCIETY

CENTENNIAL PAPERS

Standing Committee on Traffic Signal Systems (AHB25)
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Traffic Signal Systems Research: Past, Present, and Future Trends

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HISTORY OF THE TRAFFIC SIGNAL SYSTEMS COMMITTEE

Background

The Traffic Signal Systems Committee is concerned with the management of signalized intersections, the many different systems and technologies involved in their operation, and the varied groups of users in the multiplicity of environments in which signal systems function. Over the years, the Committee has served as one of the principal forums on signal control and has stimulated many currents in research that have had transformative impact on the industry.

The history of traffic signal systems, and of the shifting interests of the community of researchers interested in them, can be defined in terms of the impacts of new technologies. Signal systems themselves are a technological solution to the traffic issues of the early twentieth century. Most of the bedrock concepts of operation originated in the era of analog computing: actuation, coordination, and traffic-responsive control (*1*). The advent of computers offered new means to optimize signal timing and led to the development of central systems that could manage traffic control in large urban areas. The first of these was in Toronto in the 1960s (*2*), with numerous other cities following suit. Research in this era focused on new methods of optimizing signal timing. Among the earliest NCHRP reports is research into developing "digital-computer-controlled" signal systems for smaller cities (*3*). Other NCHRP research of this era included forays into adaptive control. The Urban Traffic Control Systems (UTCS) project, led by FHWA, also took place in this era. Among many other legacies, the UTCS vision of different "generations" of control technology persisted for many years that followed (*4*).

Solid-state electronics and microprocessors were developed in the 1970s, lead to increasingly capable field equipment. Current standards for traffic cabinets and controllers originated in this era. NCHRP research in the 1970s and early 1980s examined the selection of traffic control systems and continued development of signal control algorithms, following onto the work done under the UTCS project. By the end of the 1980s, the traffic industry had produced enough innovations to warrant an NCHRP synthesis (*5*) of these new features. At the beginning of the 1990s, "closed-loop" systems that permitted remote management began to emerge. NCHRP research of the 1990s included a study of the impacts of coordination on capacity (*6*).

Entering the Twenty-First Century

The last decade of the twentieth century saw major changes come with the proliferation of affordable personal computing and the growth of communication systems and of the internet. In January 1999, the Committee's discussion topics included adaptive control and interfacing signal controllers with simulation. At the end of the 1990s, the concept of *Hardware-in-the-Loop Simulation* (HILS) had made it possible to connect real-world controller hardware to traffic simulations (*7*). The 1999 meeting also introduced the formation of an AASHTO/ITE/NEMA joint committee to oversee the development of the Advanced Traffic Controller Cabinet architecture. The summer meeting of that year shifted focus to transit priority, bus priority, and development of new algorithms to support multimodal objectives.

The Committee's 2001 Action Plan identified several task forces that spearheaded workshops, outreach programs, and developed states of the practice. These previous task forces were focused on development of traffic signal hardware and associated infrastructure to bring greater connectivity and efficiency to traffic signals.

The Adaptive Traffic Signal Control Task Force planned workshops on adaptive traffic control systems (ATCS), identified strategies to integrate ATCS into small-to-medium size signal networks, and facilitated development of outreach to agencies. The Manual and Publications Task Force developed objectives and a timeframe for a Primer on Traffic Signal Systems. The Traffic Control Systems Review Task Force reviewed an FHWA update of the Traffic Control Systems Handbook.

Various states of the practice were developed, including bus priority at signalized intersections, vehicle detection devices, communications networks for traffic signal systems. The committee also investigated objectives and various measures of effectiveness for traffic signal timing and recommended future studies and methodology enhancements. Additionally, lists were developed concerning procurement of system software and computer hardware and impact of future ITS infrastructure.

The Committee's Triennial Strategic Plan listed two goals in 2001. The first was to provide a forum and clearinghouse for the research, development, verification, and dissemination of best practices and fundamental principles for planning, implementing, managing, and operating traffic signals and integrated transportation management systems. The second was to promote traffic signal systems within integrated urban and regional systems that improve mobility, accessibility and livability, provide safety, and maximize the quality of the environment. Additional relevant in 2001 included improving the safety and capacity of the system; integration of different modes; making the transportation system more seamless; addressing the shortage of transportation personnel; and making better investment decisions.

The 2017 Triennial Strategic Plan presented the following mission: to advance the state of the practice in planning, designing, operating, managing, and maintaining traffic signal systems by developing an understanding of relevant issues associated with traffic signals, sharing that knowledge with the professional community, and fostering future research.

These visions from 2001 and 2017 offer an opportunity to reflect on what has remained constant and what has changed, two decades into this century. Both statements emphasize the sharing of knowledge with the professional community, including both researchers and practitioners. In 2001, more of the objectives focused on specific technologies. This is still somewhat true today, with the difference being that many of the technologies have changed. The 2017 objectives are more general, perhaps reflecting on the rapidly changing state of technology, which seems to be accelerating in recent years. At the same time, the promise of new technologies can be balanced against an increasing cognizance of what transportation systems mean for the communities they serve. To that end, recent years have seen movement toward a multimodal focus and of matching operational objectives within the context of operation.

Growth of the Committee

At the 2011 Annual Meeting, the Committee had four subcommittees: Simulation, Architecture, Research, and Signal Timing. In the 2012 Summer Meeting, some subcommittees were added while others revised their titles, with six in total: Signal Timing, Technology and Standards, Asset Management, Multimodal Systems, Simulation and Research. In 2016, a seventh subcommittee on Education was added, and most recently, the Asset Management subcommittee expanded its focus to include performance measurement.

In the past two decades, the size of the TRB Annual Meeting has grown tremendously in terms of the number of attendees and the number of papers submitted for review. This Committee has seen its review assignments increase from 27 in 1999 to a peak of 120 submissions in 2017.

CURRENT ISSUES AND TRENDS

The *Signal Timing Manual*

A major accomplishment in the past twenty years for the Committee was the development of the *Signal Timing Manual* (*8*), now in its second edition (*9*). The vision for this manual was to provide a resource similar to other canonical engineering practice documents like the *Highway Capacity Manual*, oriented toward traffic signal timing. This effort was the result of one of the younger members (Peter Koonce) asking colleagues in the Traffic Signal Systems Committee why the profession did not have such a document to serve as a record of established best practices. This question sparked interest, leading to the FHWA funding an unsolicited proposal as a competitive procurement based loosely on short courses developed for the University of Washington's Technical Assistance Program. In 2008, two years after the TRB meeting where the initial question was raised, the first *Signal Timing Manual* was produced, written by Kittelson and Associates, Purdue University, the Texas Transportation Institute, and the University of Maryland. The success of the first draft led to the development of a robust Research Problem Statement by members of the Committee, which led to the funding of a NCHRP project to develop the second edition, which was published in 2015 as an NCHRP report.

The second edition of the Signal Timing Manual (STM2) was produced as a standalone document based on user feedback on the first edition. The STM2 introduces an outcome-based approach to signal timing, which encourages the practitioner to develop signal timing based on the operating environment, users, user priorities by movement, and local operational objectives. Performance measures are then used to assess how well the objectives are being met. Once the objectives and performance measures are established, timing strategies and timing values can be chosen. The final steps of the process involve implementation and observation (i.e. determining if the timing strategies and values are working), as well as sustaining operations that meet the operational objectives through monitoring and maintenance. Key features of this edition include addition of four new chapters for more advanced users and expanded use of graphics to aid in the explanation of more complex topics.

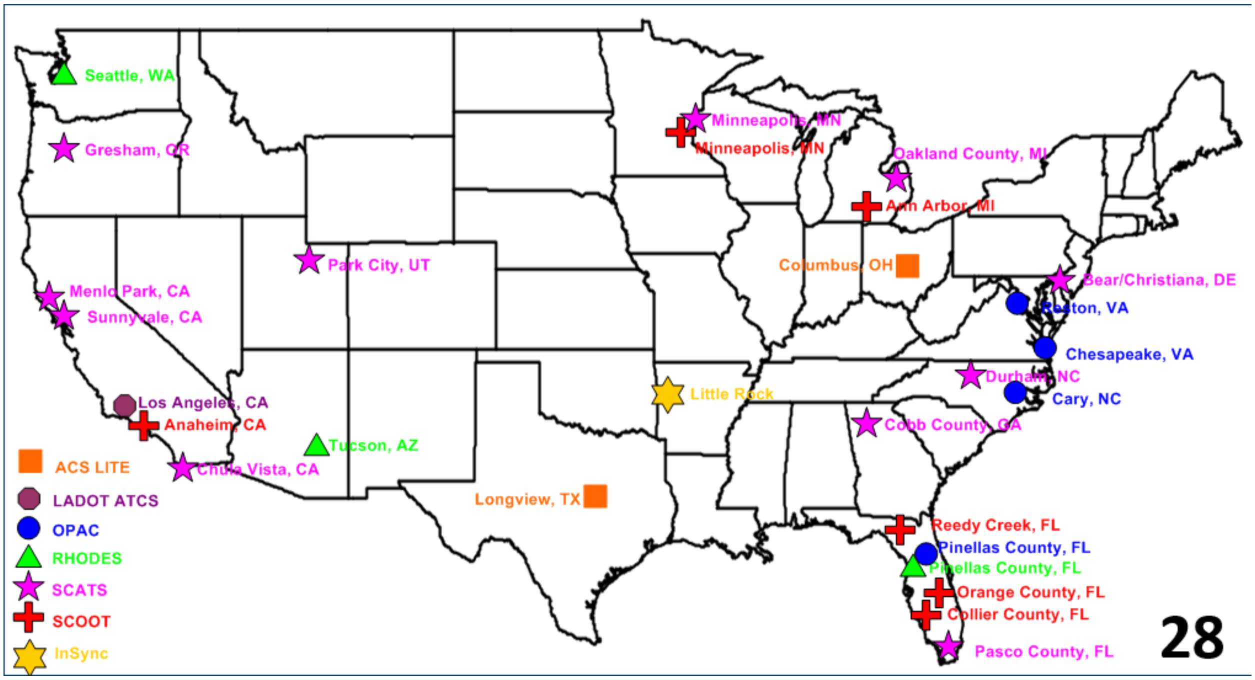
Keeping with its mission to advance the state-of-the-practice and state-of-the-knowledge related to traffic signal timing, the Signal Timing Subcommittee completes the following activities related to the Signal Timing Manual:

- Tracks use of the latest edition of the Signal Timing Manual and related courses (e.g., National Highway Institute, NHI) through periodic surveys, webinars, and download counts.
- Logs comments on the latest edition of the Signal Timing Manual and related courses (e.g., NHI) collected at TRB meetings and through a new focus group made up of committee members and friends.
- Identifies gaps in the field of traffic signal timing (e.g., best practices, needed research, etc.) that can be incorporated into future editions of the Signal Timing Manual.
- Coordinates with the Education Subcommittee to incorporate the Signal Timing Manual into educational material.

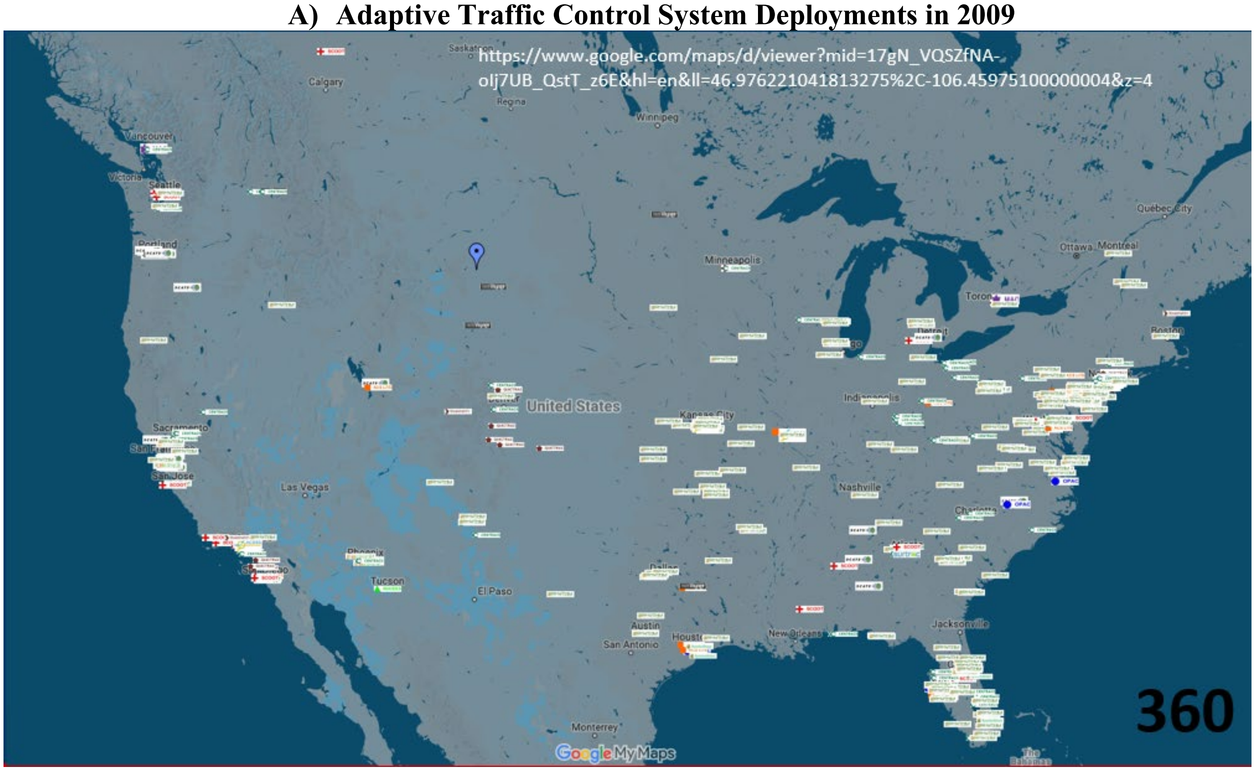
Adaptive Control

Adaptive traffic control systems (ATCS) have been in continuous use since the 1980s. The first successes of systems overseas (*10, 11*) were soon followed by a FHWA initiative (*12*) to develop ATCSs in the US through a project called Real-Time Traffic Adaptive Signal Control Strategy (RT-TRACS). The initial successes of the systems developed through RT-TRACS (13) were soon overshadowed by the limitations imposed by the lack of infrastructural readiness for such detection- and communication-intensive systems. These outcomes initiated another FHWA initiative, in the mid-2000s, with the goal of developing ATCS that would be compatible with the most common detection and communication profile of US traffic signal operators (*14*). The resulting system, ACS-Lite, had significant successes in several deployments. These successes, along with improved affordability and enhancements in communication and detection technologies, stimulated the development of new technologies and systems which flourished especially after 2010 (*15*). This development was accelerated with the adoption of ATCS technology as an FHWA Every Day Counts program focus technology.

The number of ATCSs increased from around 25 active systems in 2009 to more than 350 systems in 2019, in approximately the same number of agencies/communities (Figure 1). There are now more than 20 brands of ATCS available in North America (of which 15 are available commercially). At present, there are approximately 11,200 traffic signals controlled by ATCS in the US. This number still constitutes less than 3% of all of the traffic signals in the US. ATCSs are deployed in more than 40 states; the leading states in terms of the number of deployed systems are California, Pennsylvania, Virginia, and Florida. The largest ATCS deployment with non-commercially available technology is Los Angeles' Automated Traffic Surveillance and Control (ATSAC) system, which controls more than 4500 signals. Meanwhile, the largest ATCS deployment using commercially available technology is the SCATS system deployed in Oakland County, Michigan; this system includes more than 750 signals. In terms of the number of deployments, the InSync ATCS appears to have the largest number of deployments, numbering around 190 systems across the US. Innovation in the area of ATCS continues to be a fruitful research topic, with new ideas emerging along with the increasing amounts of data that can be obtained.



A) Adaptive Traffic Control System Deployments in 2009



B) Adaptive Traffic Control System Deployments in 2019

Figure 1. Geographical distribution of ATCS deployments in North America

Performance Measurement

Performance measurement is an essential activity in any engineering endeavor, as it permits other activities to be evaluated. For many years, the management of traffic signal systems was evaluated almost entirely by labor-intensive manual processes, such as floating-car studies, and information about the system's day-to-day operation was informed more by public complaints and anecdotal reports than by quantitative information. In recent years, the types of performance measures available and now in common use have transformed dramatically.

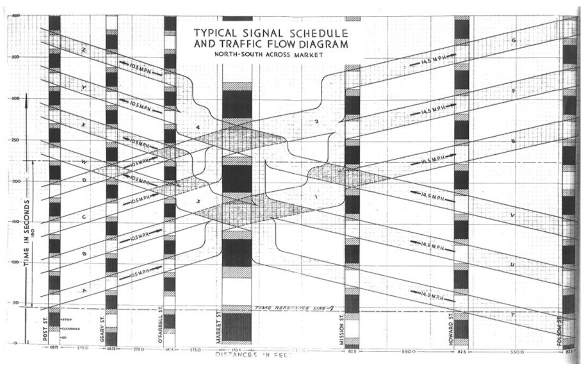
In the mid-2000s, the concept of "high-resolution data" took shape in separate research projects sponsored by Indiana DOT (at Purdue University), and by Minnesota DOT (at the University of Minnesota) (*16,17,18*). These studies both required the real-time collection of the occupancy states of individual detectors, which needed to be cross-referenced against the active signal state during each moment of operation. In Indiana, vehicle detector performance evaluation was the initial application, while Minnesota's research examined queue length and arterial travel time estimates. Researchers quickly realized that the data used in these studies could be developed into useful performance measures (*19*). Early studies showed potential for assessing progression, capacity allocation, and pedestrian phase performance, among other applications. These metrics would later come to be known as Automated Traffic Signal Performance Measures (ATSPM).

These initial state DOT efforts were expanded by NCHRP research. NCHRP 03-79A introduced several additional use cases (*20*), while NCHRP 03-90 applied the high-resolution data concepts to oversaturation performance measures (*21*). A Pooled Fund study including 12 agencies and FHWA continued development of ATSPM, solidifying the previous research in a series of comprehensive reports (*22,23*). This work was followed up by implementation guidance under NCHRP 3-122. Much of the research that went into the development of ATSPM through these studies was peer-reviewed by this Committee and presented in TRB Annual Meetings over the years.

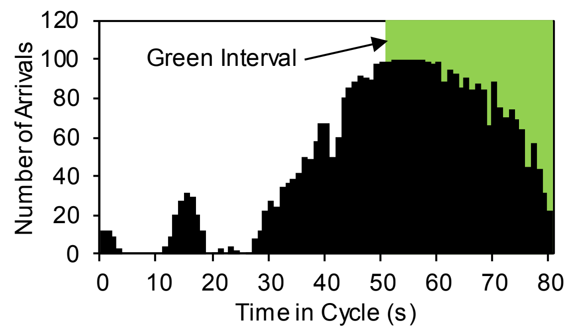
Meanwhile, the high-resolution data concept won acceptance from signal vendors. At the time of writing, at least seven different manufacturers had implemented data collection in their controller products, in addition to several external data logger products. Another important component of this work was the development of software to deliver ATSPM to the user. Starting in 2012, Utah DOT began developing an open-source web-based system (*24*), which has been deployed by numerous agencies and spurred development of vendor systems. ATSPMs were selected as a focus technology in the third round of the FHWA Every Day Counts program (2016-2018) and are becoming a widely-accepted tool for signal management.

Figure 2 shows an evolution of graphical performance measures for signal progression. The oldest of these is the time-space diagram (Figure 2a), which had become a standard tool for signal timing by the 1920s (*25*). This illustrates the relationship between anticipated traffic flow and signal timing for a static timing plan. In the 1960s, flow-based models of traffic led to the development of the cyclic flow profile (Figure 2b), which shows the distribution of vehicle arrivals on a signal approach relative to the cycle (*26,27*). The likelihood that the signal will be green can be superimposed. The "Purdue Coordination Diagram" (PCD) is one of the metrics enabled by high-resolution data and developed during NCHRP 3-79A (*28*). This chart (Figure 2c) examines individual vehicle arrival times relative to the signal state at that moment, allowing the outcomes of the traffic control to be directly visualized and evaluated (*29*).

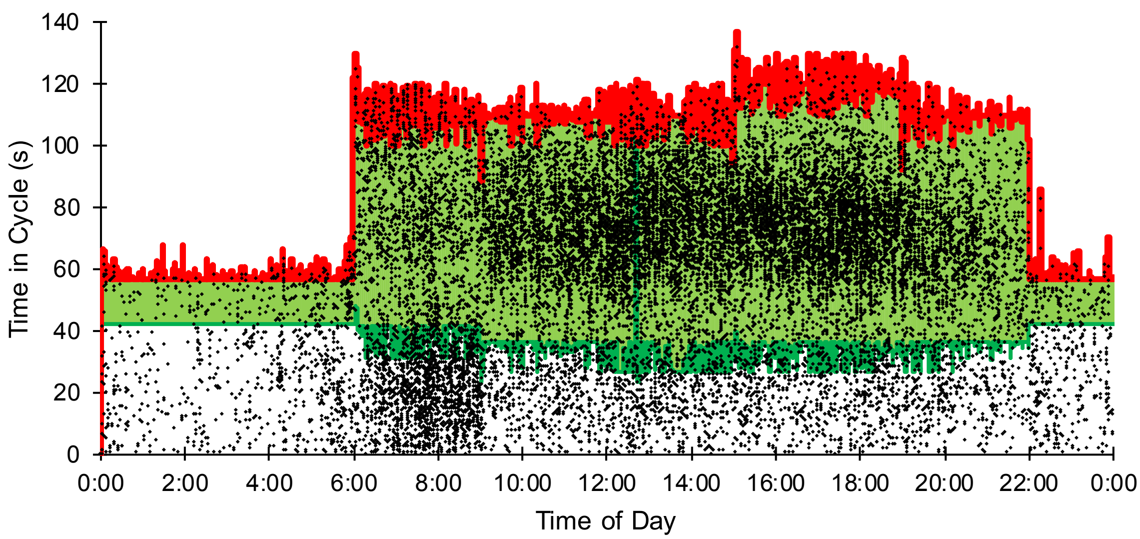
In parallel to these developments, innovations in traffic monitoring have enabled new approaches to outcome assessment; Around 2006, automatic vehicle identification (AVI) data in the form of Bluetooth MAC address matching emerged as a means of measuring and tracking travel times along corridors and across networks (*30,31*). A few years later, automatic vehicle location (AVL) data crowdsourced from mobile devices enabled the development of commercial services who have marketed a variety of analytical products to enable travel monitoring on an unprecedented scale (*32,33*). In the past few years, the raw vehicle position data has been applied to evaluate and adjust signal timing (*34,35*). Recent studies using data from rideshare services in China shows the scalability of this data concept (*36*). Future development of similar data sources is a current research trend. In the 2019 Annual Meeting, an entire poster session was devoted to uses of vehicle trajectory data.



(a) Time-space diagram from the 1920s.



(b) Flow profile concept from TRANSYT.



(c) The “Coordination Diagram”, developed under NCHRP 3-79A.

Figure 2. Evolution of intersection analytics for evaluating smooth flow.

Source of Figure 2a:
https://commons.wikimedia.org/wiki/File:Typical_Signal_Schedule_and_Traffic_Flow_Diagram,_North-South_across_Market_(1929).png

Multimodality

Traffic signal systems are a component of the built urban environment, and the task they serve has an outsized role in determining the character of travel in those environments. In recent decades, as cities have experienced a reversal of the mid-twentieth century trend of urban flight, there has been expanded interest in developing transportation systems to better accommodate all modes of traffic in urban areas. The National Association of City Transportation Officials (NACTO) has emerged as a leading organization with a mission toward building safe, sustainable, accessible, and equitable cities. In addition to their activities toward producing guidance on urban street design, NACTO has proven to be a valuable resource for information exchange on multimodal signal operations.

The Committee has engaged in several activities along this front. Inspiration from Summer Meetings in Portland (2003) and Toronto (2004) saw a focus on Transit Signal Priority (TSP); Projects TCRP A-16 and A-16A sought to improve the state of the practice in TSP implementation in the US. More recently, the NTCIP 1211 standard on Signal Control priority, allowing for phase-specific priority requests, has been released (*37*) and is starting to see its implementation in control products. The Committee recently created a new subcommittee on multimodal signal operations to track such activities. Recent multimodal research in signal operations has included investigations into person-based signal timing (*38*) and automatic bicycle and pedestrian counting with existing infrastructure (*39*). NCHRP 3-133 is currently investigating strategies for non-motorized users at signalized intersections.

Objectives

For various reasons, not the least being the tendency for traffic signal management to be under resourced, it has often been necessary for practice to be rather ad hoc. In recent years, a conversation among members of the community has developed around the most fundamental questions—namely, what the basic objectives of signal operation should be, how these should be attained, and how success can be measured. This move toward objectives-based management reflects a growing trend toward accountability seen in other domains of transportation engineering and public works.

Within the context of traffic signal management, the thinking on the objectives of a signal program have coalesced around the concepts of goals, objectives, strategies, and tactics, executed within a certain context, and documented in a management plan. This idea has been advanced by FHWA in its signal-related activities and is reflected in the creation of recent guidance for ATCS and ATSPM (*40,41*).

Education

Over the last 15 years, formal higher education has gone through a bit of a renaissance, in that it is no longer acceptable for an instructor to simply present information to a group of willing students and expect that material to be passively absorbed. Presentation of material in various methods is encouraged, as well as delivery of content through multiple modes of media, as it is well known that all of us learn differently. As this change has taken place in the formal channels of higher education, such a shift has taken place within the interests of the committee. While education was always certainly an area of interest of for the academics involved in the group, several efforts by the committee, as well as its members and friends, have shown a commitment to education on multiple levels.

In the late 2000s, several committee members were involved with the development of the Mobile Hands-On Signal Timing Training (MOST), a novel approach to learning about traffic signal timing (*42*). This collection of modules and experiments was unique in the field when released. In contrast to conventional passive instruction, this course emphasized a student focus in which learning takes place through active experimentation, collecting and analyzing data, and drawing conclusions about what makes good signal timing practice. These exercises were incorporated into a student-centered textbook, *Traffic Signal Systems Operation and Design*, released in 2012 authored by two long-time committee members (*43*). 2010's Summer Meeting, hosted by Michael Kyte and the University of Idaho, focused on education, and included discussions on current educational best practices and how to implement them within different areas of technical focus.

More recently, in 2015 a formal Education subcommittee was implemented, charged with focusing on educational issues for all areas that touch the Committee's reach. This new subcommittee has seen participation from university, consultant, and agency staff, including engineers and technicians. Since inception, the subcommittee has worked with other professional groups to develop educational modules for consumption at the university and professional level and hosted presentations and discussions on a variety of topics germane to the charge of the subcommittee, including newer educational methods, modules available for technician training through ITE/IMSA, and NHI course topics.

From a Competition to Research

The Committee has served as fertile ground for the genesis of new research projects, sometimes by unexpected means. The 2012 Summer Meeting took place in Irvine, CA with a topic of "Traffic Signals and the Operational Effects of Roadway Geometrics: How to get it Right". A portion of the meeting was dedicated to a competition to develop signal timing for a diverging diamond interchange (DDI) which had recently been opened in Missouri. Recognizing that the construction of DDIs was outpacing guidance on how to operate them, the Committee decided that a competition could spur new ideas and provide guidance for practice. A contest announcement was sent out in April for the competition at the Summer Meeting, along with details on the geometrics for the interchange, problem statement, judging criteria, and rules of the competition.

Four teams accepted the challenge and presented their solutions at the meeting. A "skeptics' squad" of committee senior members served as judges. The competition stimulated lively discussion among presenters, judges, and the other meeting participants. This Summer Meeting topic and competition eventually led to the development of project NCHRP 03-113: "Guidance for Traffic Signals at Diverging Diamonds and Adjacent Intersections" (*44*). One of the teams that participated in the Summer Meeting competition was selected to carry out the NCHRP project, which ultimately developed guidance now being presented to practitioners across the country through a webinar series.

ADDRESSING FUTURE CHALLENGES

The Accelerating Growth of Information

The future of transportation is a variable landscape, and opinions about how future transportation will look and operate, and how it may transform the world. Traffic signal systems will play a role in how this transformation may take shape. Right now, roadside infrastructure is beginning to communicate with select equipped vehicles and pedestrians. This capability will continue to evolve in the coming years. A critical item for this Committee in the future will be to shape how this comes to pass in the traffic signal space. It will be important to answer critical questions about how signal infrastructure will relay accurate information to users in all modes about its operation in a method that is reliable and trusted.

New data sources will continue to emerge, and existing data sources will continue to evolve and yield new uses. Since the initial work on ATSPMs, new metrics have continuously been developed by academia and both the public and private sectors. The near future is likely to see a push to expand these concepts into more automated features; several commercial platforms have begun to develop and implement such strategies. It is likely that ATSPM data will one day be integrated with connected vehicle data. In the future, this Committee will endeavor to stay abreast of such advancements and identify how they will apply to the operation of traffic signal systems as we move into a more connected environment.

The Future of Urban Traffic Control

Urban traffic control, defined in its most general way, represents a process of managing movements of various traffic users to ensure conflict-free passage along their intended paths. Traffic signal systems are used to visually convey messages to the drivers as to whether they have the right of way through intersections of conflicting paths. New advances in wireless communication and computational technologies are opening the door to new technologies, such as connected vehicles (CVs) and automated vehicles (AVs). These will likely inspire new methods of controlling traffic. For example, the wireless exchange of Signal Phasing and Timing (SPaT) messages between controllers and vehicles represents the first time that visual communication (between the signal displays and drivers) has been replaced by radio communication (between signal controllers and vehicle computers) for general vehicles. It should be noted that radio communication has been used previously for special users (e.g., emergency vehicles, public transportation vehicles, and pedestrians via audio signals). CV technology extends this concept, through a special communication protocol, to the entire equipped fleet.

These CV advancements have extended the range at which the signal messages could be shared with vehicles. This extended communication range has in turn opened opportunities for various new traffic control methods to impact vehicular paths farther from the intersection box. Such applications include Green Light Optimized Speed Advisory (GLOSA) systems (*45*), also known as Eco-Driving systems (*46, 47*), which can be used to reduce or increase vehicular speeds to reduce number of vehicular stops at the intersections (providing that there is a full compliance from the vehicular fleet). Unlike older signal priority systems that request priority for only a few vehicles of a special class, CV technologies enable a multi-class execution of the priority requests which can be used to address a variety of policy goals in multimodal environment (48).

In future, the concept of priority-request, reservation-based driven, traffic signal control could be extended to *all* vehicles in the traffic stream, possibly rendering visual signal displays completely unnecessary (*49*). These display-free control methods, sometimes called Autonomous Intersection Management (*50*), inherently include GLOSA-like handling of vehicular movements which translates the signal message from a “digital” format (1-green-GO, 2-yellow-STOP/GO, 3-red-STOP) to an “analog” format (drive at a specific speed between 10-45 mph). Research has already shown that reservation-based traffic control systems can bring significant benefits to the traveling public, compared to the conventional signal system designs (*50*). Furthermore, when combined with reversible lanes (*51*), innovative phasing (*52*), and alternative geometrical intersection designs, the control of traffic streams in urban network may become very different from today’s conventional “within-the-intersection-box” traffic signal control. Some of the latest research efforts show that when a reservation-based control is implemented along the entire road infrastructure and combined with flexible utilization of the roadway surface, such systems can significantly reduce both number of vehicular conflicts and traffic delays and stops (*53*).

CONCLUSION

The Traffic Signal Systems Committee has served as a forum for research into the management and operation of signal systems and has helped to foster and coordinate research on these topics. This paper provided a brief overview of past, present, and future focuses of the Committee and of the groups that have taken shape within its subcommittees. The past several years have seen growing momentum on several of these fronts, with research having an increasing impact on practice. The prospects for future research topics are exciting, with numerous innovations looming on the horizon, whether in the context of traffic signal systems as they are known today or in the intersection management systems of the future.

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